US009190712B2

(12) **United States Patent**
Hu et al.

(10) **Patent No.: US 9,190,712 B2**
(45) **Date of Patent: Nov. 17, 2015**

(54) **TUNABLE ANTENNA SYSTEM**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 265 days.

(21) Appl. No.: **13/366,142**

(22) Filed: **Feb. 3, 2012**

(65) **Prior Publication Data**

US 2013/0201067 A1 Aug. 8, 2013

(51) **Int. Cl.**

H01Q 21/30	(2006.01)
H01Q 1/50	(2006.01)
H01Q 1/24	(2006.01)
H01Q 9/04	(2006.01)
H01Q 9/42	(2006.01)
H01Q 5/321	(2015.01)
H01Q 5/328	(2015.01)

(52) **U.S. Cl.**

CPC ***H01Q 1/243*** (2013.01); ***H01Q 5/321*** (2015.01); ***H01Q 5/328*** (2015.01); ***H01Q 9/0421*** (2013.01); ***H01Q 9/42*** (2013.01)

(58) **Field of Classification Search**

CPC H01Q 5/321

See application file for complete search history.

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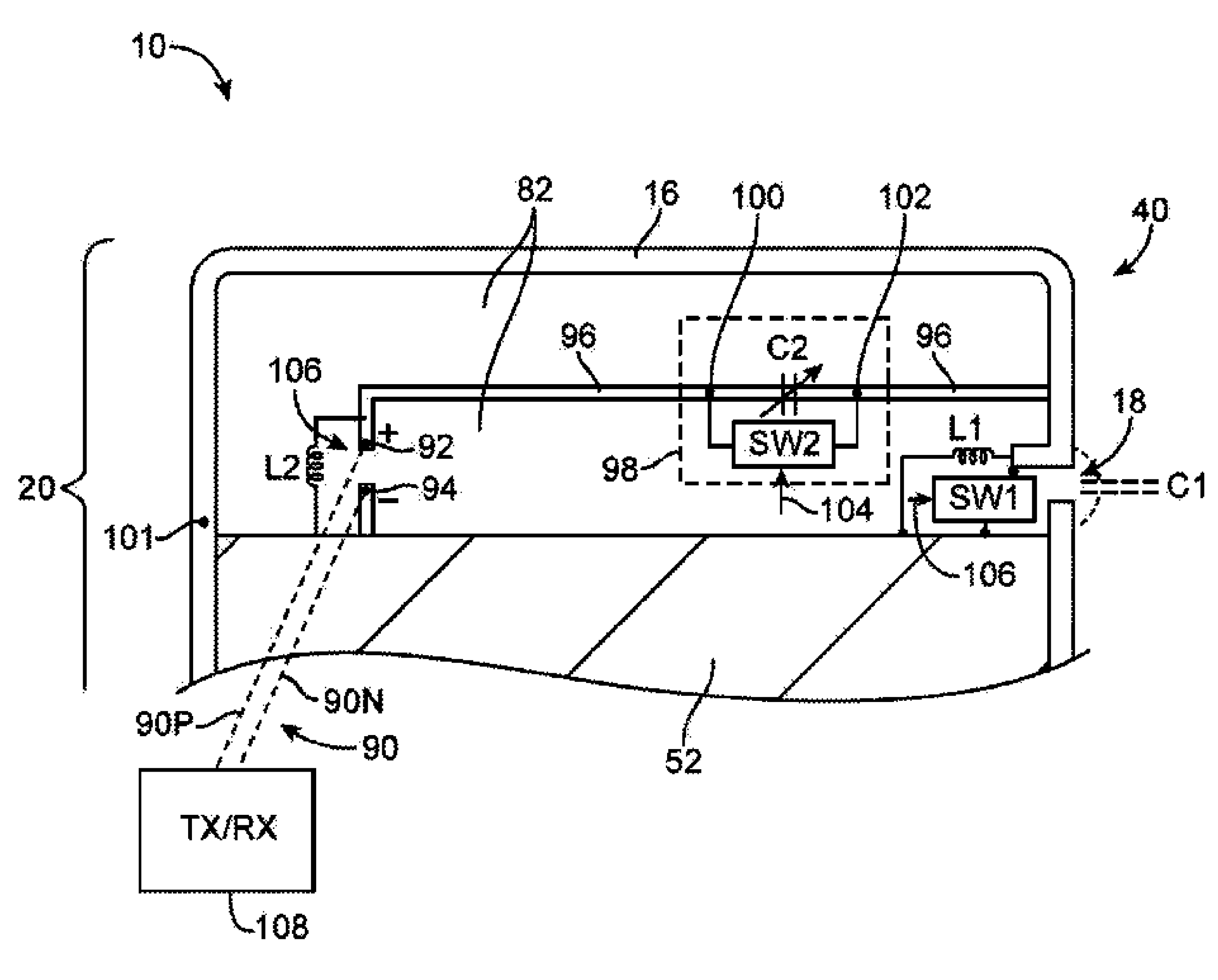
(57) **ABSTRACT**

An electronic device antenna may be provided with an antenna ground. An antenna resonating element may have a first end that is coupled to the ground using an inductor and may have a second end that is coupled to a peripheral conductive housing member in an electronic device. The peripheral conductive housing member may have a portion that is connected to the ground and may have a portion that is separated from the ground by a gap. The gap may be bridged by an inductor that couples the second end of the antenna resonating element to the antenna ground. The inductor may be bridged by a switch. A tunable circuit such as a capacitor bridged by a switch may be interposed in the antenna resonating element. The switches that bridge the gap and the capacitor may be used in tuning the antenna.

23 Claims, 11 Drawing Sheets



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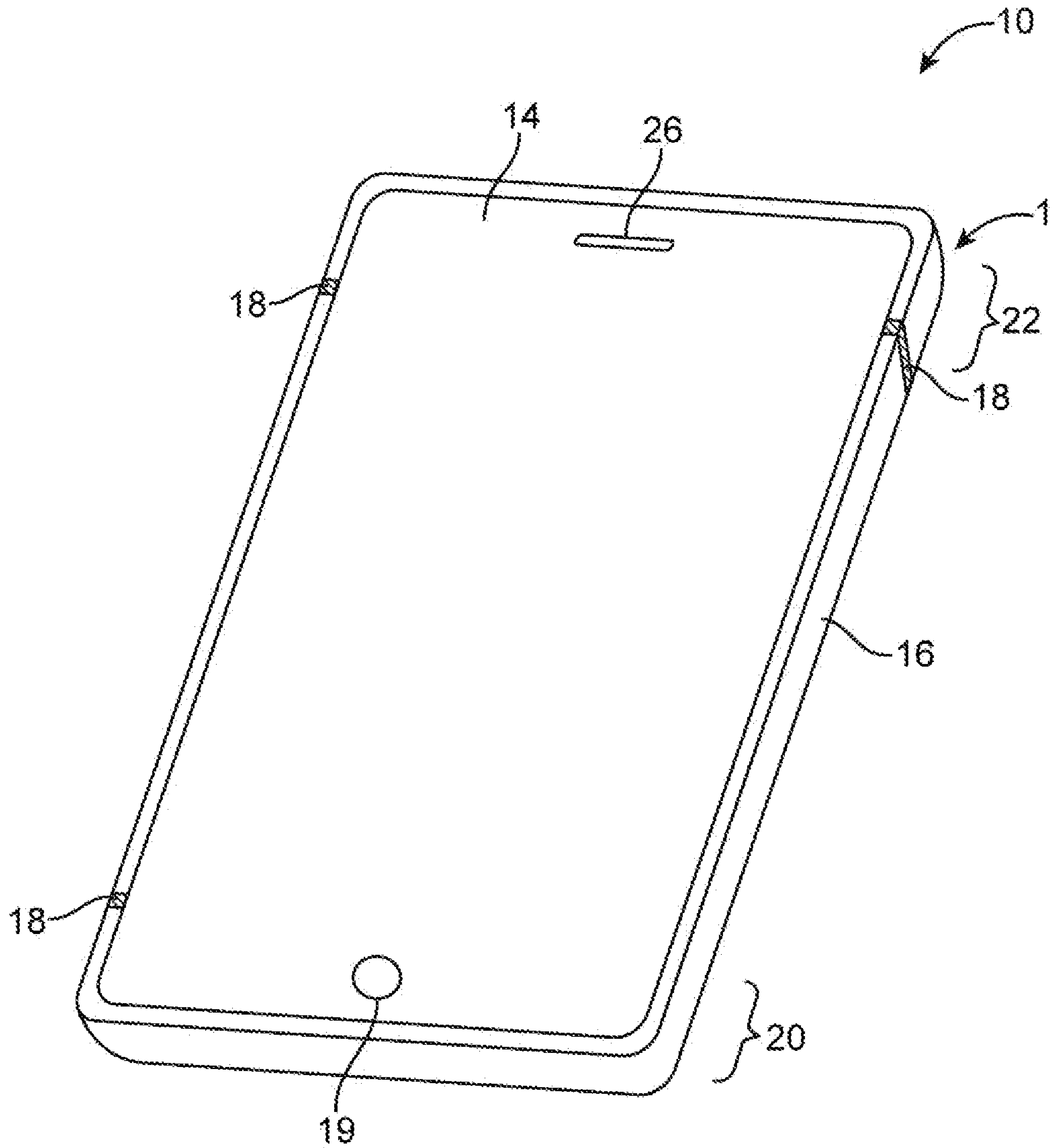
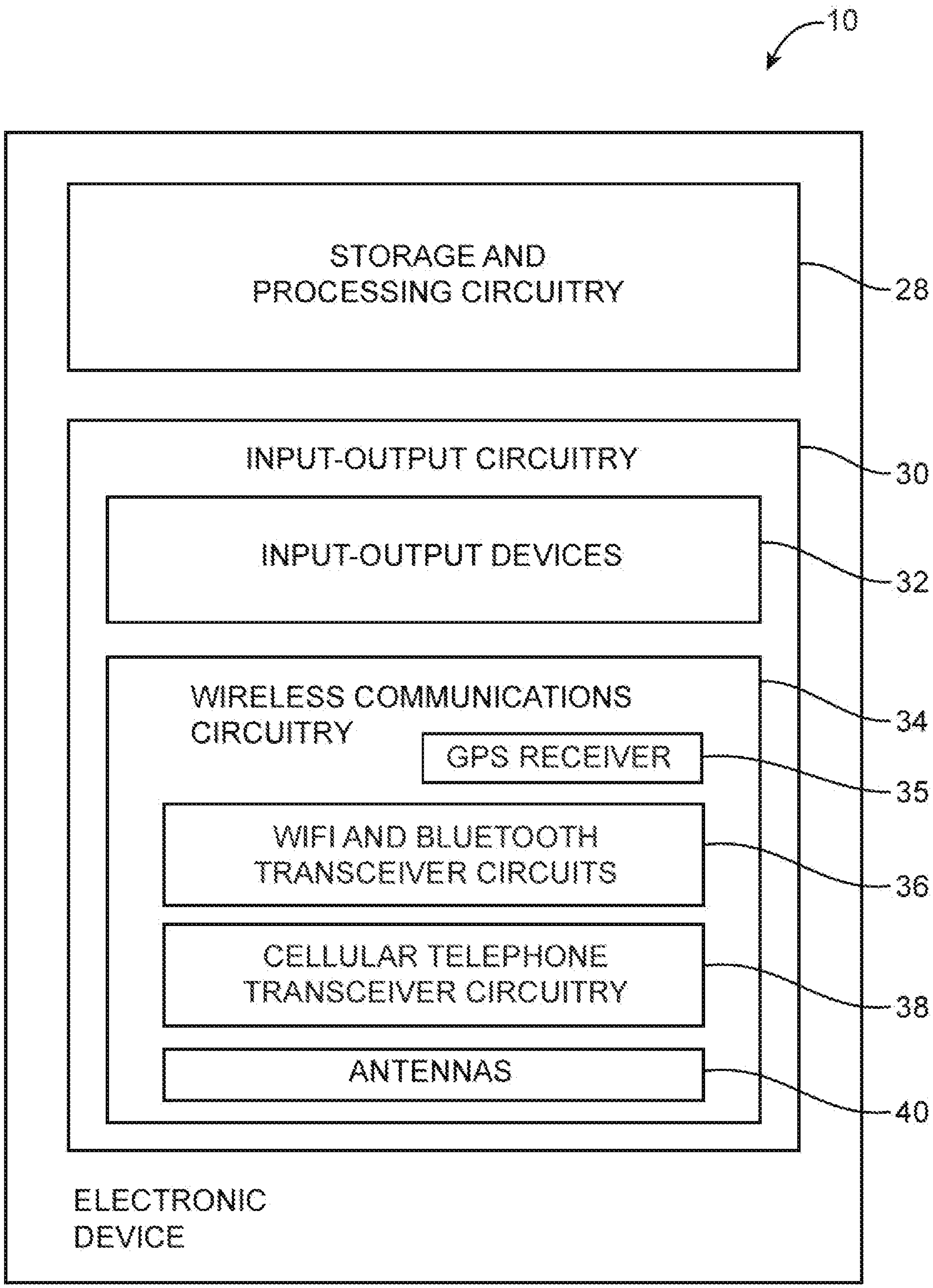


FIG. 1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INPUT-OUTPUT CIRCUITRY
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INPUT-OUTPUT DEVICES
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35
WIFI AND BLUETOOTH
TRANSCEIVER CIRCUITS
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CELLULAR TELEPHONE
TRANSCEIVER CIRCUITRY
38
ANTENNAS
40
ELECTRONIC
DEVICE

FIG. 2

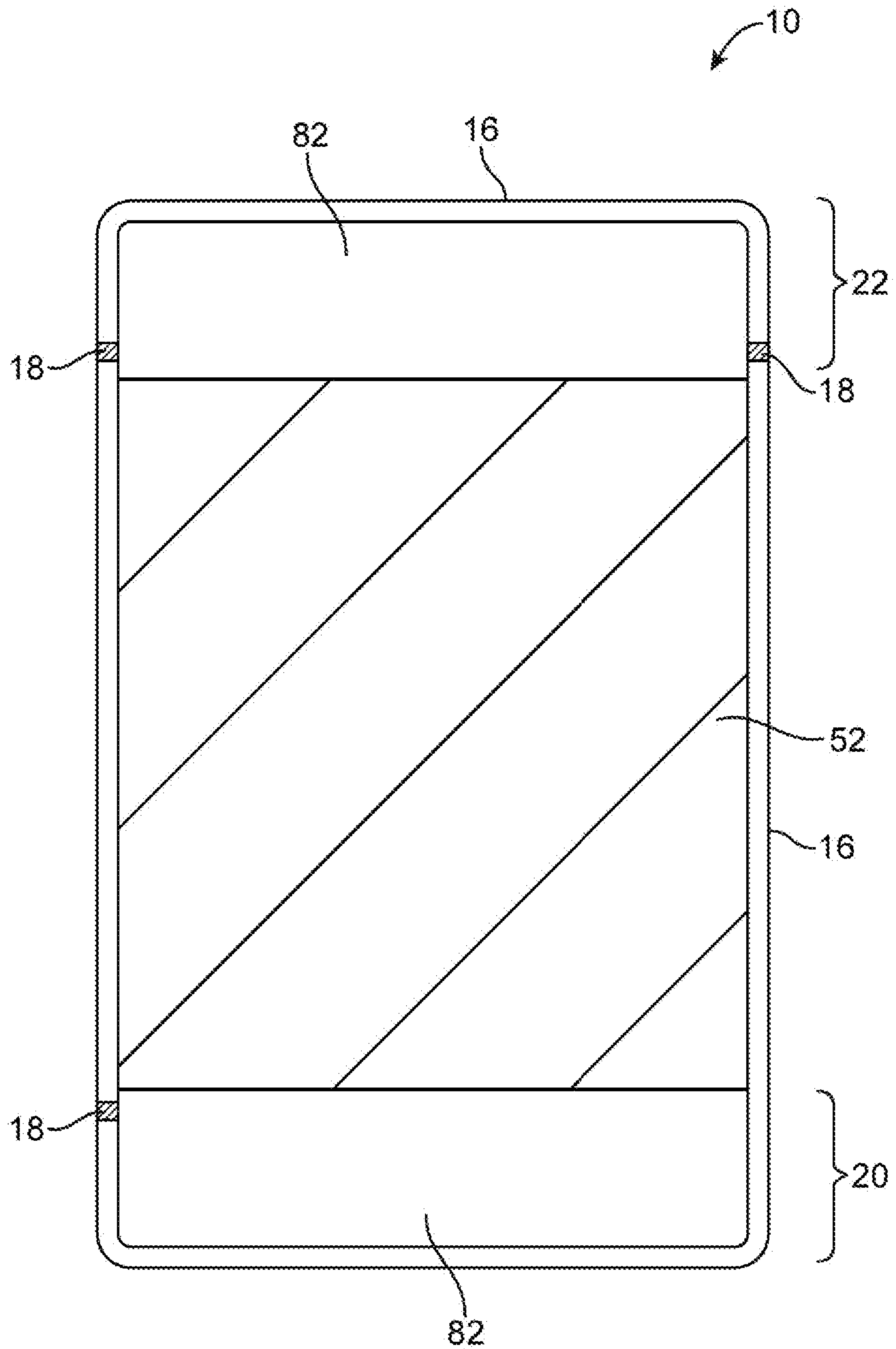
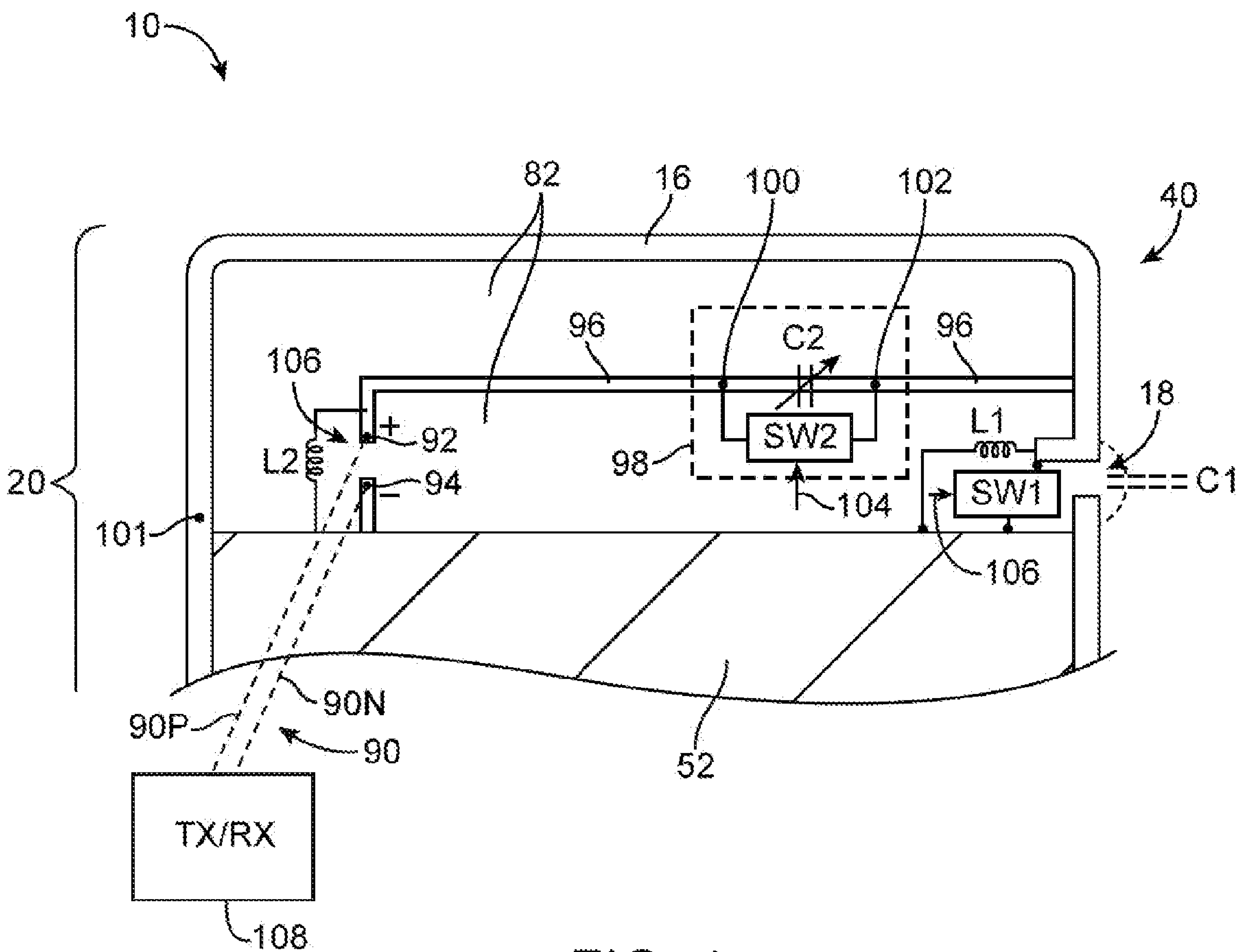


FIG. 3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90P
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TX/RX
108

FIG. 4

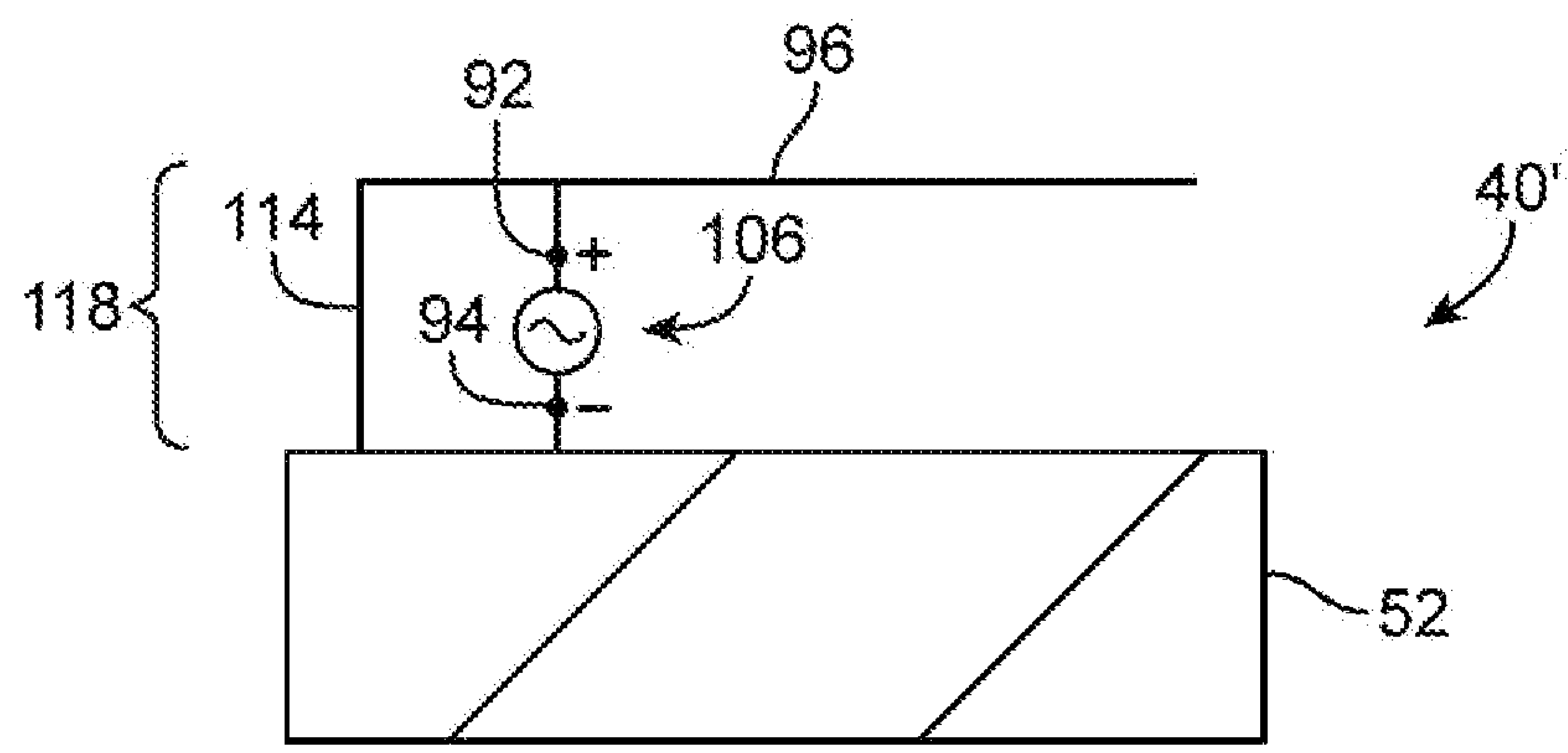


FIG. 5

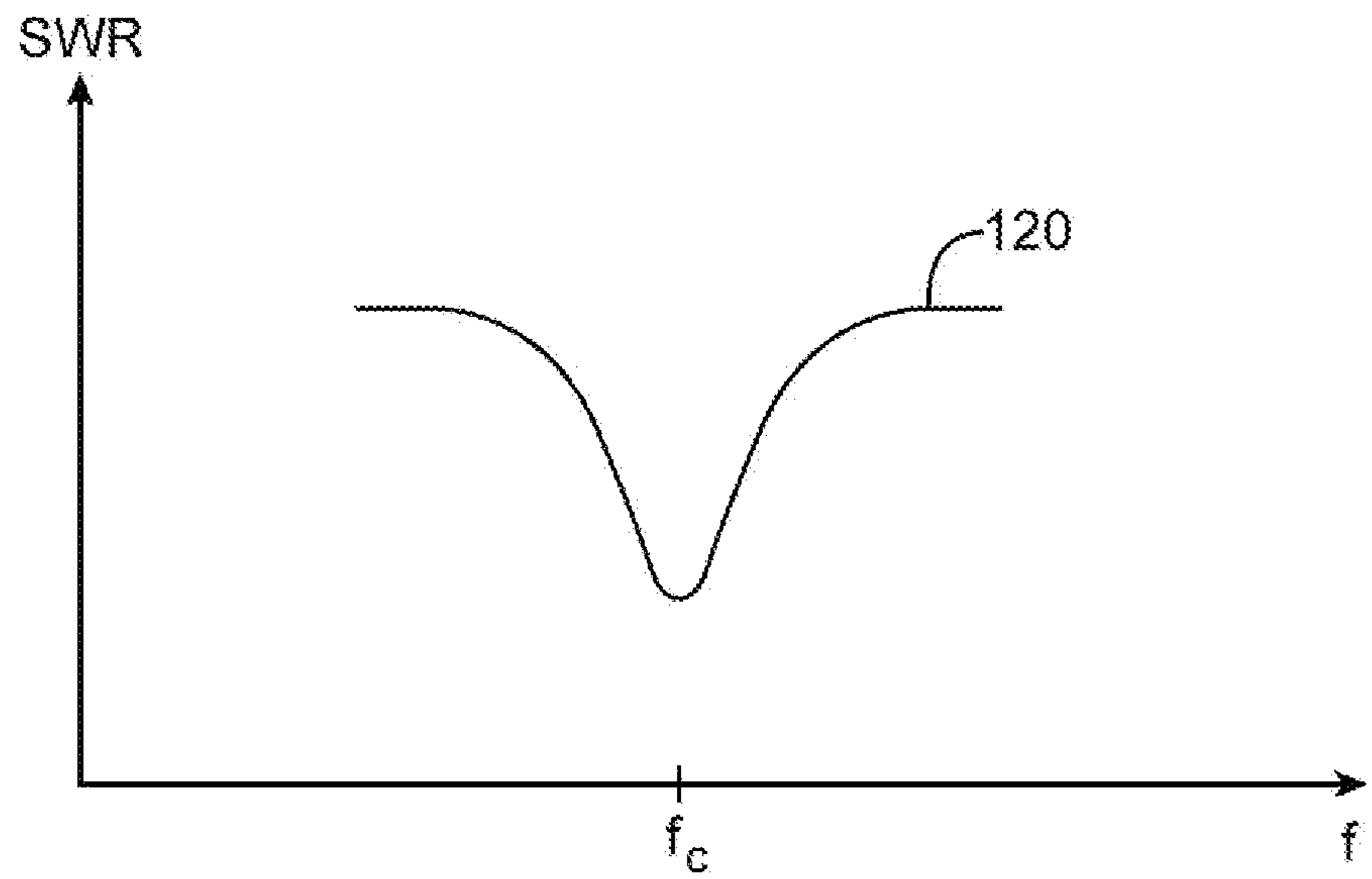


FIG. 6

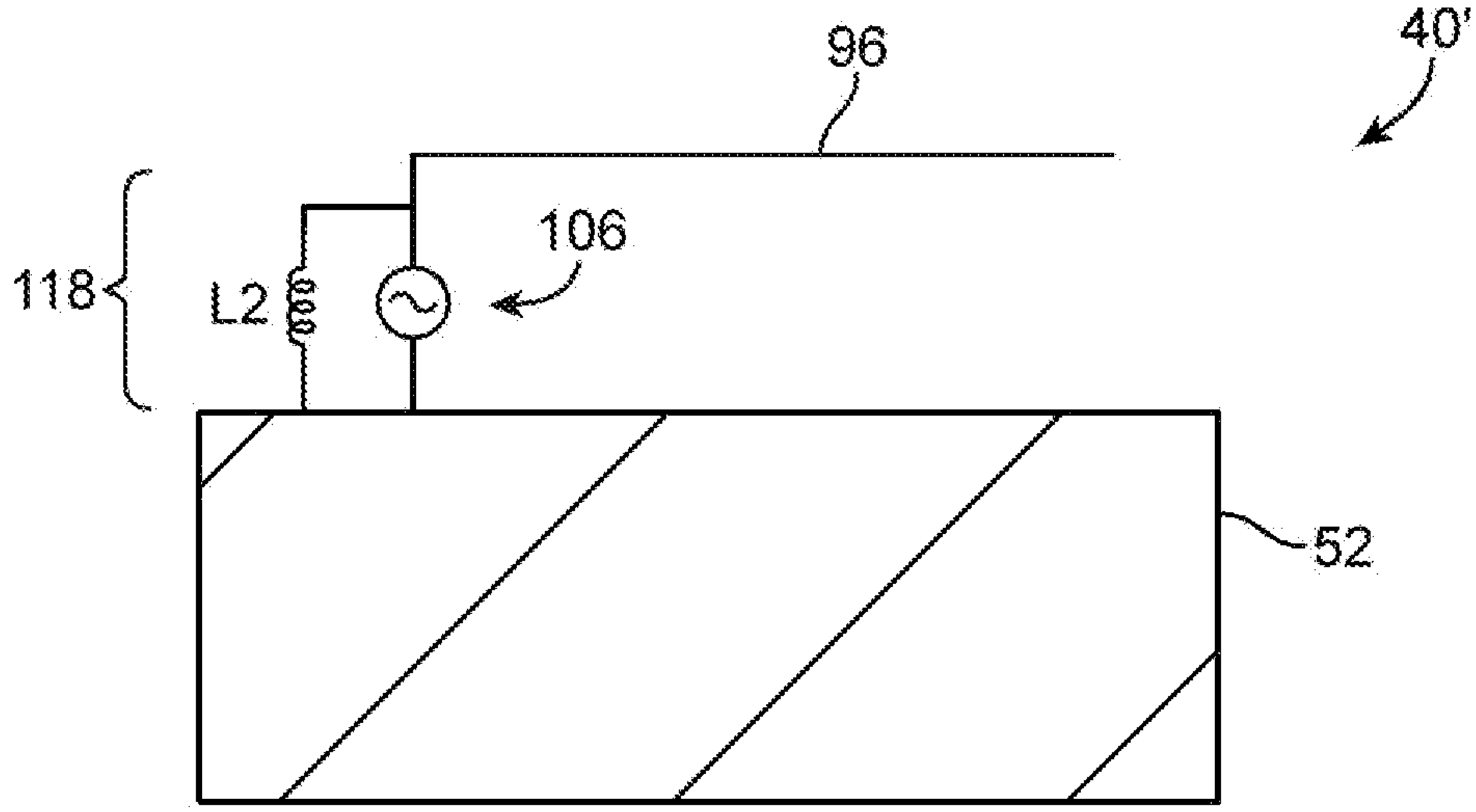


FIG. 7

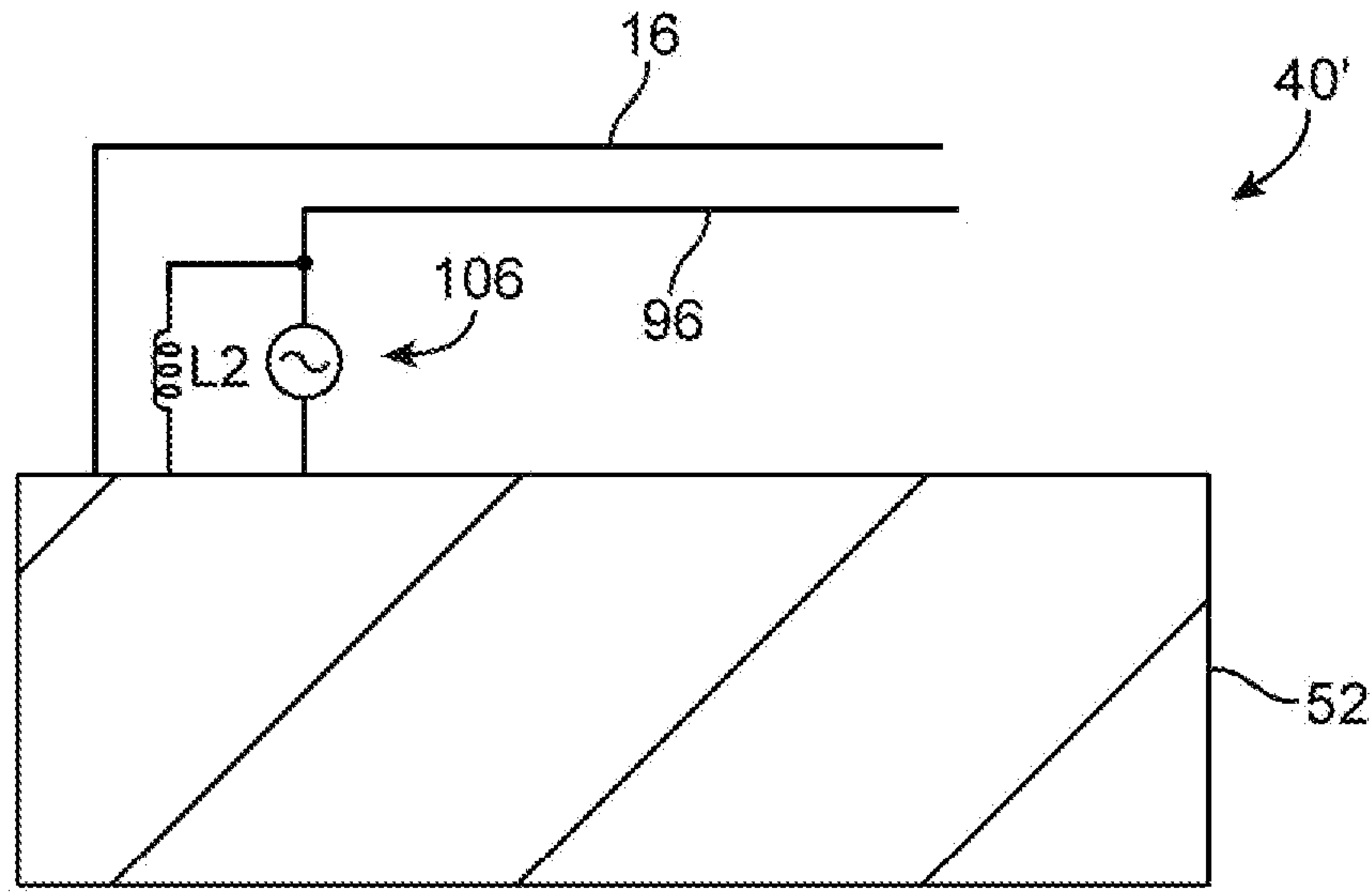


FIG. 8

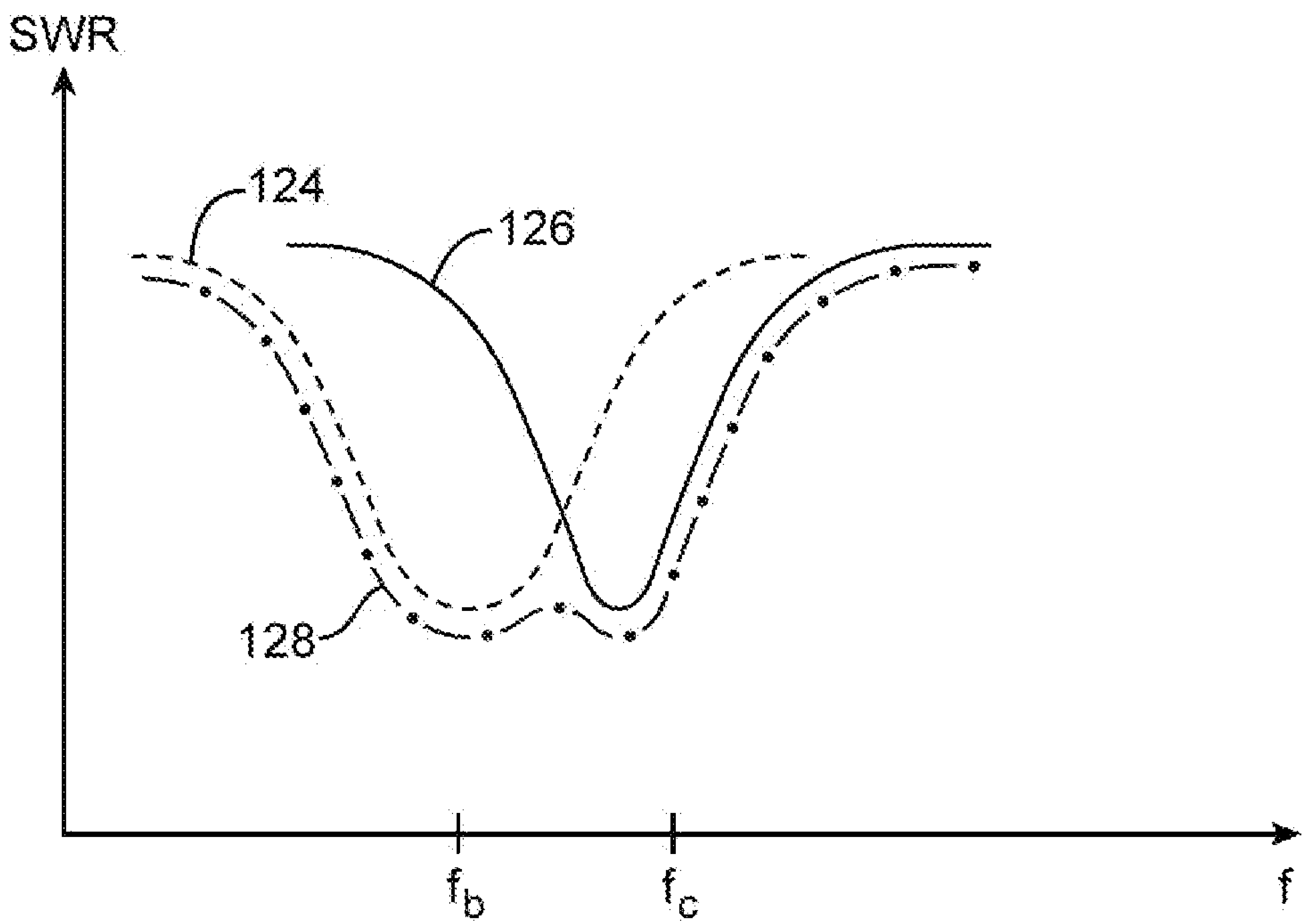


FIG. 9

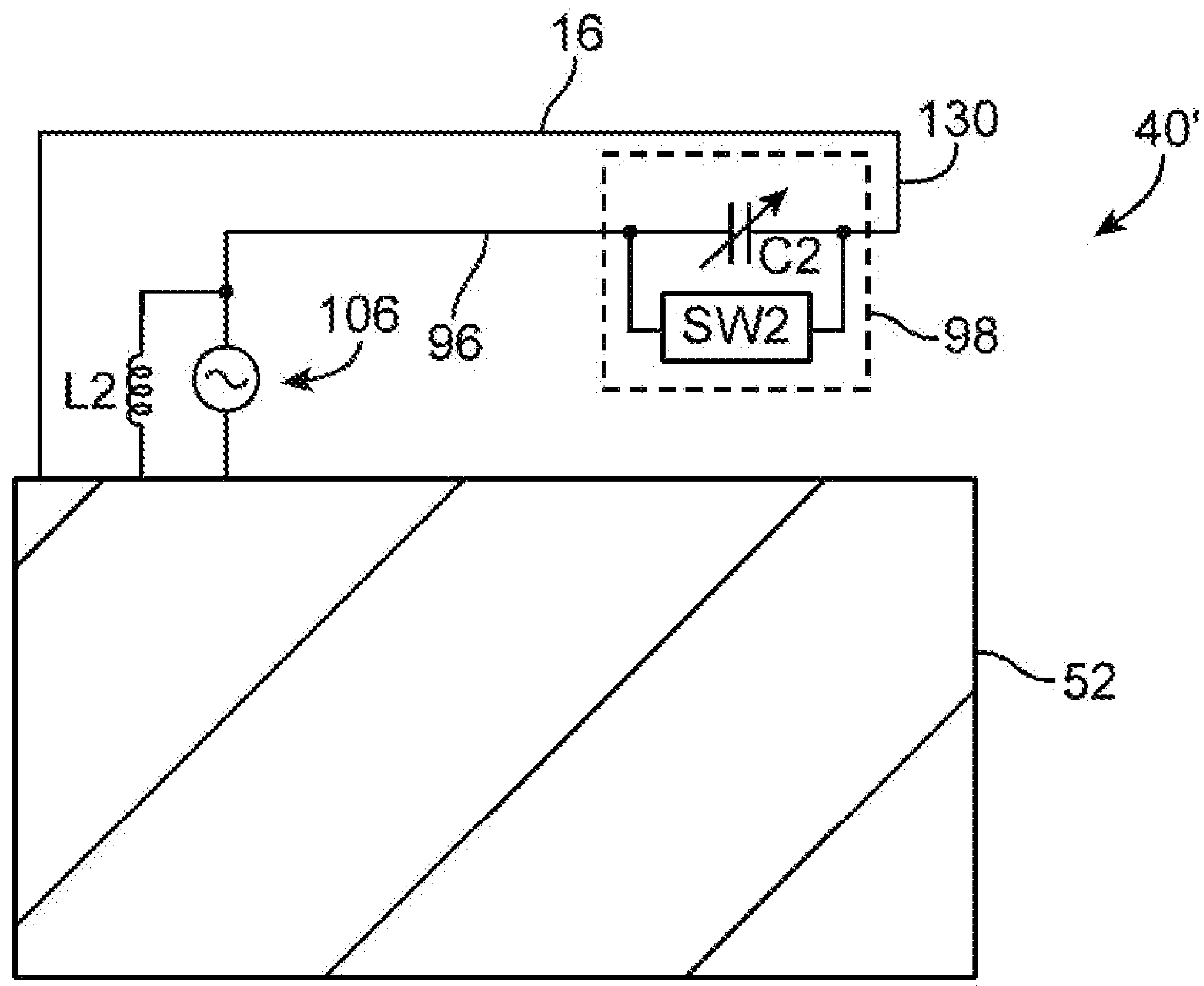


FIG. 10

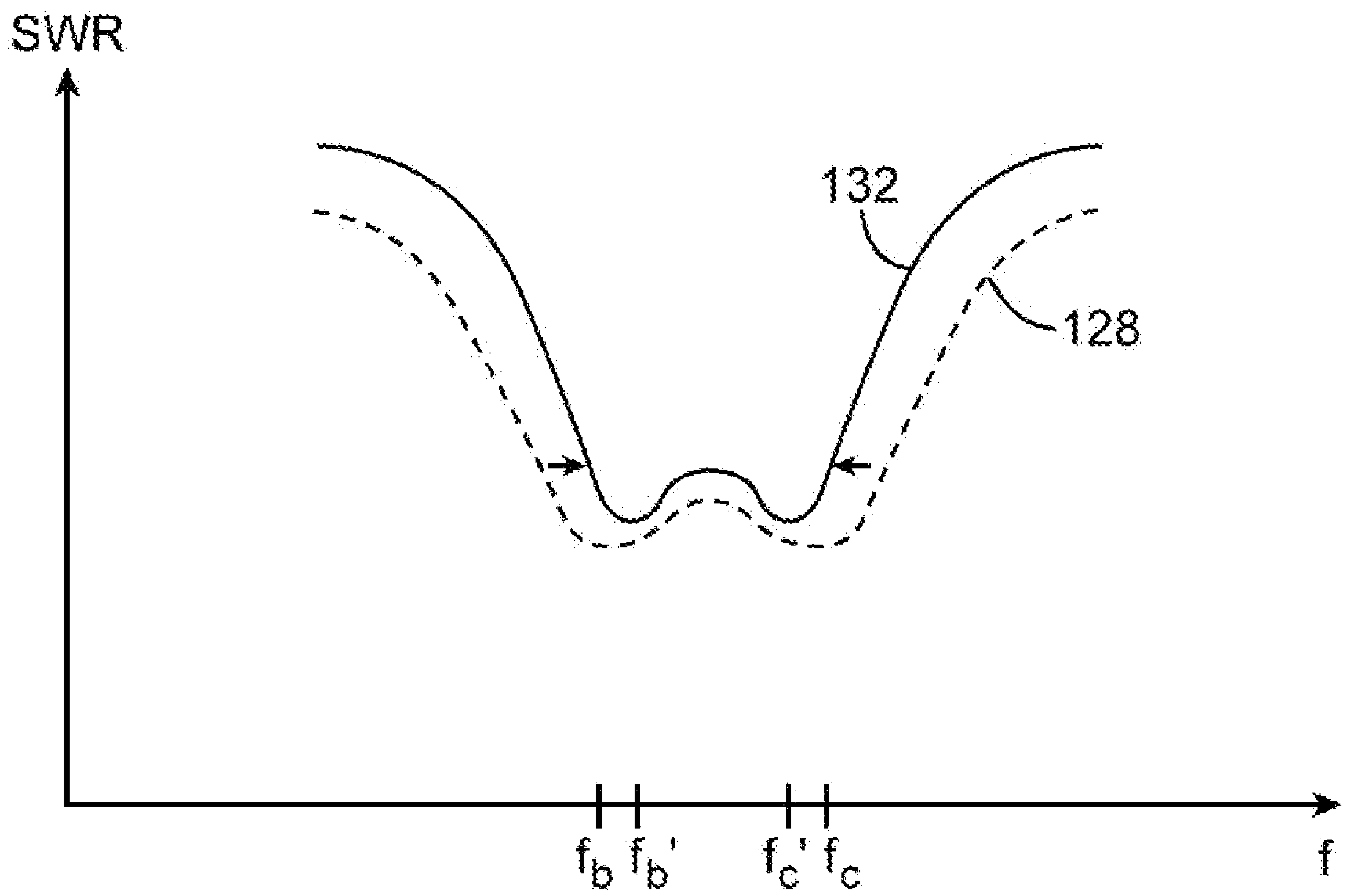


FIG. 11

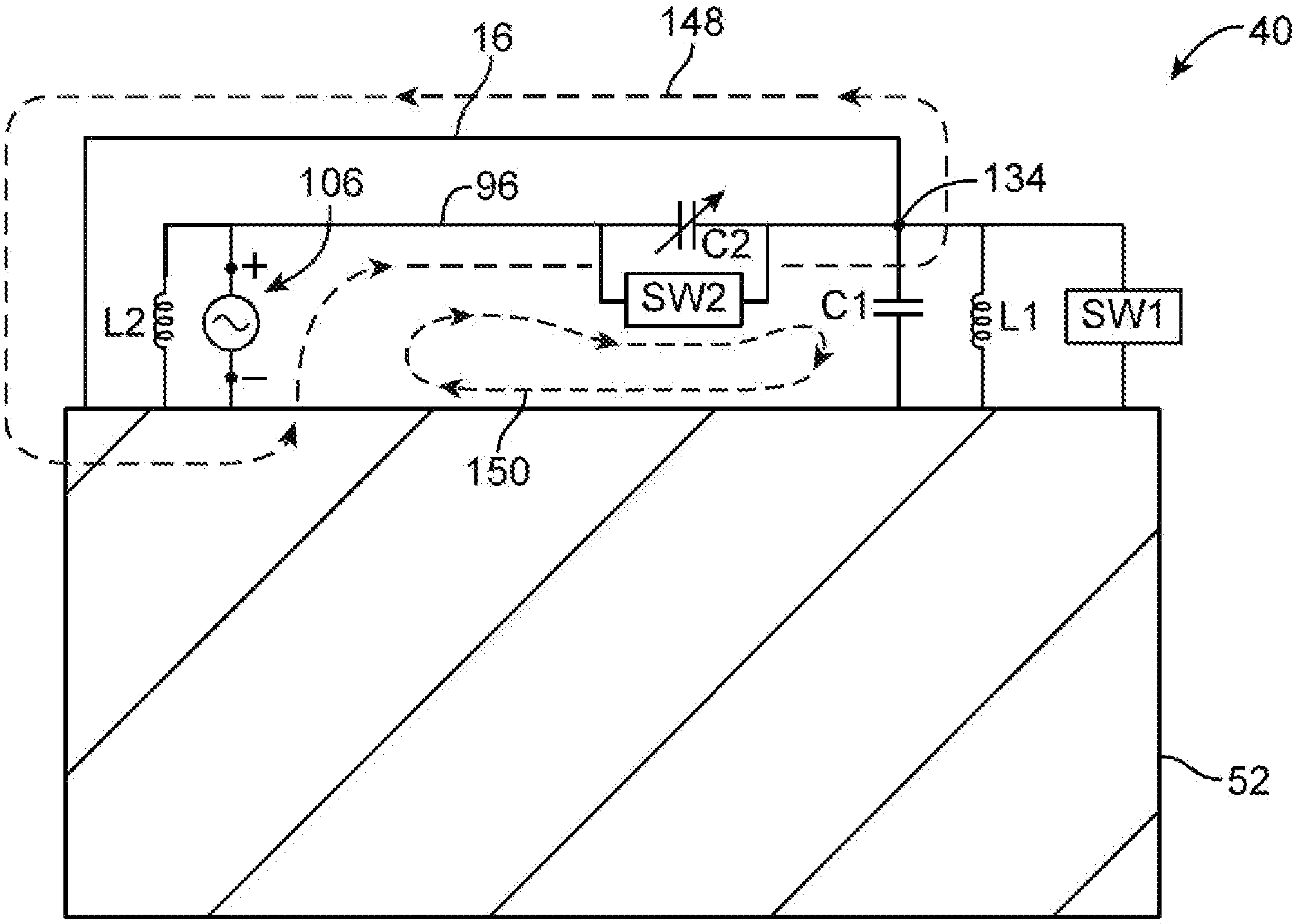
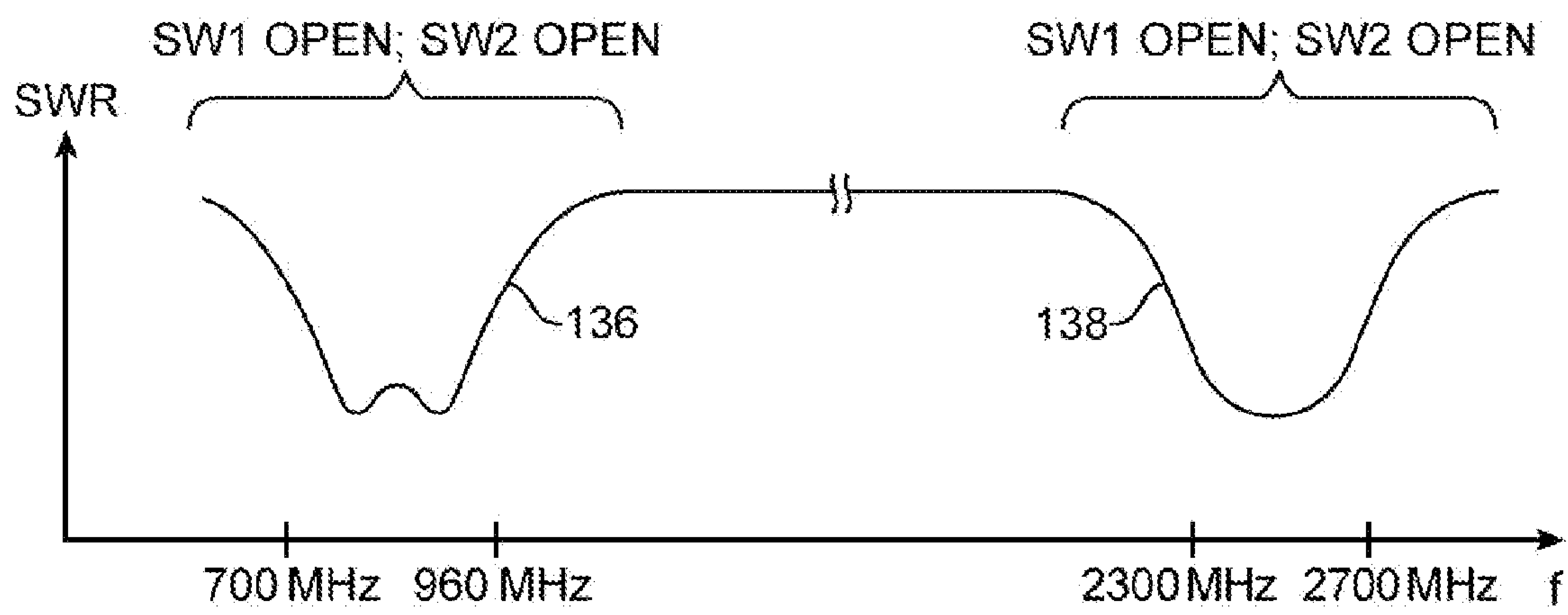


FIG. 12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SW1 OPEN; SW2 OPEN
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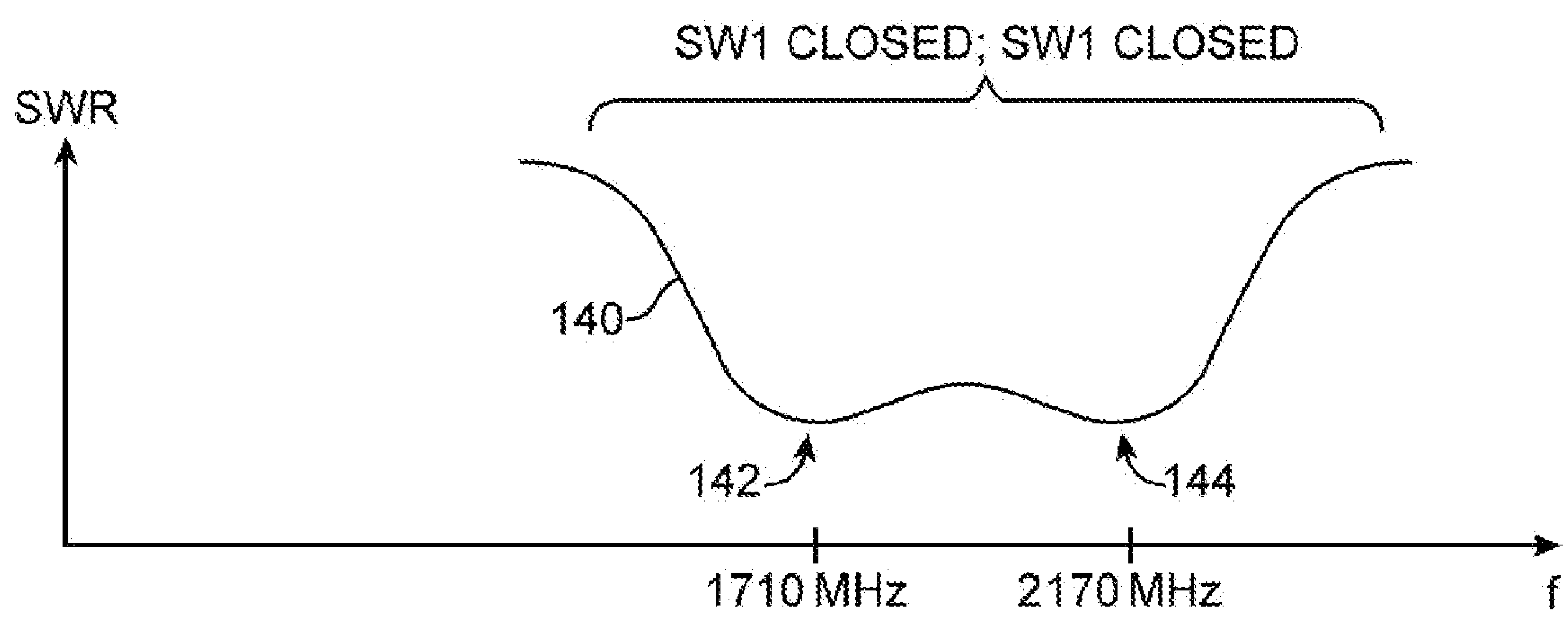
136
138
700 MHz
960 MHz
2300 MHz
2700 MHz
f

FIG. 13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142
144
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f

FIG. 14

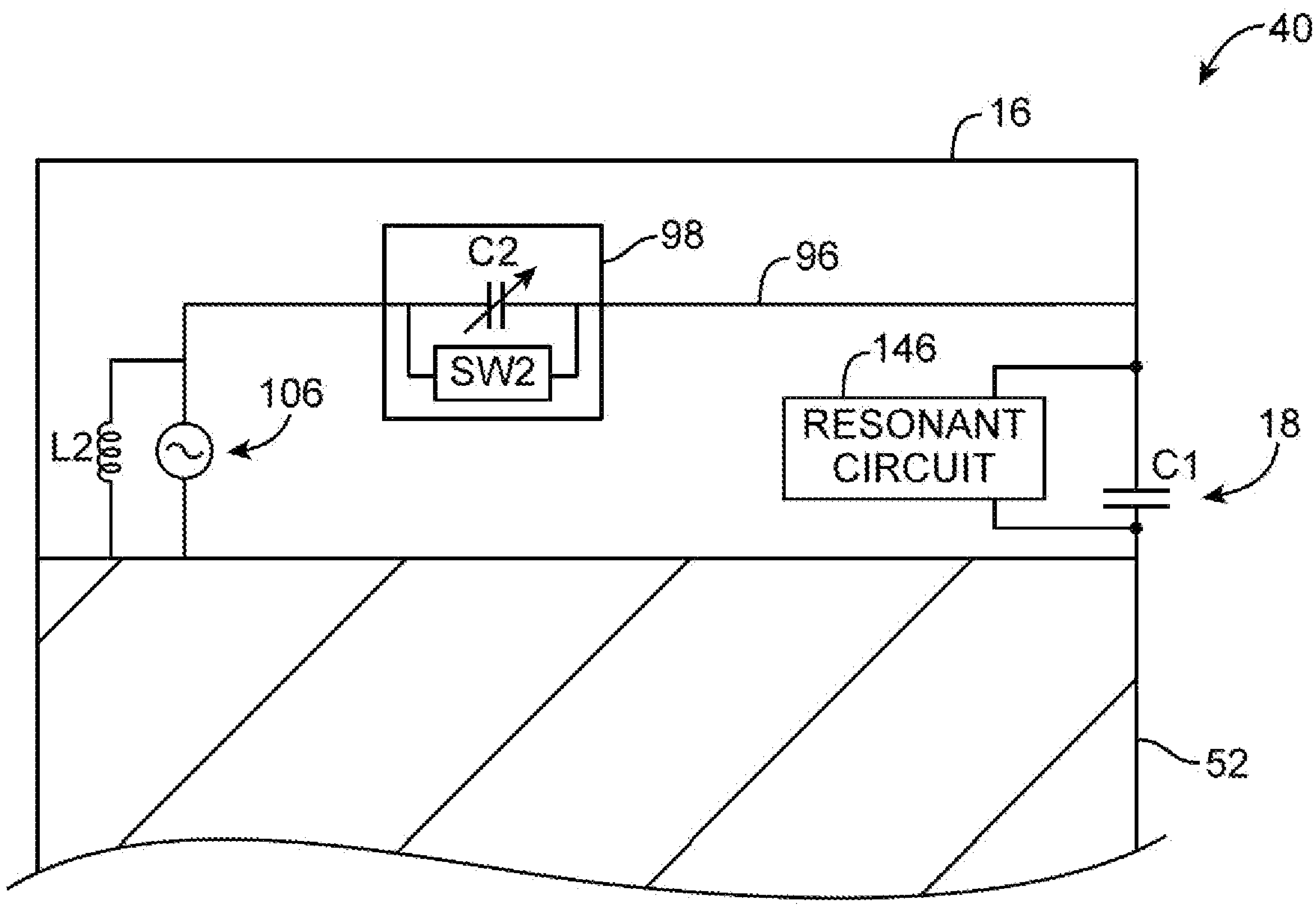

FIG. 15

TUNABLE ANTENNA SYSTEM

BACKGROUND

This relates generally to electronic devices, and more particularly, to antennas for electronic devices with wireless communications circuitry.

Electronic devices such as portable computers and cellular telephones are often provided with wireless communications capabilities. For example, electronic devices may use long-range wireless communications circuitry such as cellular telephone circuitry to communicate using cellular telephone bands. Electronic devices may use short-range wireless communications circuitry such as wireless local area network communications circuitry to handle communications with nearby equipment. Electronic devices may also be provided with satellite navigation system receivers and other wireless circuitry.

To satisfy consumer demand for small form factor wireless devices, manufacturers are continually striving to implement wireless communications circuitry such as antenna components using compact structures. At the same time, it may be desirable to include conductive structures in an electronic device such as metal device housing components. Because conductive components can affect radio-frequency performance, care must be taken when incorporating antennas into an electronic device that includes conductive structures. Moreover, care must be taken to ensure that the antennas and wireless circuitry in a device are able to exhibit satisfactory performance over a range of operating frequencies.

It would therefore be desirable to be able to provide improved wireless communications circuitry for wireless electronic devices.

SUMMARY

Electronic devices may be provided that contain wireless communications circuitry. The wireless communications circuitry may include radio-frequency transceiver circuitry and antenna structures. The antenna structures may form one or more antennas.

An electronic device antenna may be provided with an antenna ground. An antenna resonating element may have an arm with a first end that is coupled to the ground using an inductor and a second end that is coupled to a peripheral conductive housing member in an electronic device. The peripheral conductive housing member may have a portion that is connected to the ground and may have a portion that is separated from the ground by a gap. The gap may be bridged by an inductor that couples the second end of the antenna resonating element to the antenna ground. The inductor may be bridged by a switch. A tunable circuit such as a capacitor bridged by a switch may be interposed in the antenna resonating element arm. The switches that bridge the gap and the capacitor may be used in tuning the antenna.

Further features of the invention, its nature and various advantages will be more apparent from the accompanying drawings and the following detailed description of the preferred embodiments.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a perspective view of an illustrative electronic device with wireless communications circuitry in accordance with an embodiment of the present invention.

FIG. **2** is a schematic diagram of an illustrative electronic device with wireless communications circuitry in accordance with an embodiment of the present invention.

FIG. **3** is a diagram of an illustrative electronic device of the type shown in FIG. **1** showing how structures in the device may form a ground plane and other antenna structures in accordance with an embodiment of the present invention.

FIG. **4** is diagram of an illustrative tunable antenna in accordance with an embodiment of the present invention.

FIG. **5** is a diagram of an illustrative inverted-F antenna structure for an antenna in accordance with an embodiment of the present invention.

FIG. **6** is a graph of antenna performance associated with use of the antenna structure of FIG. **5** in accordance with an embodiment of the present invention.

FIG. **7** is a diagram of illustrative inverted-F antenna structures with an inductor path in parallel with an antenna feed for an antenna in accordance with an embodiment of the present invention.

FIG. **8** is a diagram of illustrative antenna structures with an inductor path in parallel with an antenna feed and an L-shaped parasitic antenna resonating element for an antenna in accordance with an embodiment of the present invention.

FIG. **9** is a graph of antenna performance associated with use of the antenna structures of FIG. **8** in accordance with an embodiment of the present invention.

FIG. **10** is a diagram of illustrative antenna structures of the type shown in FIG. **8** that have been provided with a bypassable capacitor circuit for performing antenna tuning functions in accordance with an embodiment of the present invention.

FIG. **11** is a graph of antenna performance associated with use of the antenna structures of FIG. **10** in accordance with an embodiment of the present invention.

FIG. **12** is a diagram of illustrative antenna structures of the type shown in FIG. **10** that have been provided with a tuning circuit such as a switch-based tuning circuit to form an antenna of the type shown in FIG. **4** in accordance with an embodiment of the present invention.

FIGS. **13** and **14** are graphs of antenna performance associated with use of the antenna of FIG. **12** in accordance with an embodiment of the present invention.

FIG. **15** is a diagram of illustrative antenna structures of the type shown in FIG. **12** in which the switch-based tuning circuitry of FIG. **12** had been replaced with a passive resonant-circuit in accordance with an embodiment of the present invention.

DETAILED DESCRIPTION

Electronic devices such as electronic device **10** of FIG. **1** may be provided with wireless communications circuitry. The wireless communications circuitry may be used to support wireless communications in multiple wireless communications bands. The wireless communications circuitry may include one or more antennas.

The antennas can include loop antennas, inverted-F antennas, strip antennas, planar inverted-F antennas, slot antennas, hybrid antennas that include antenna structures of more than one type, or other suitable antennas. Conductive structures for the antennas may, if desired, be formed from conductive electronic device structures. The conductive electronic device structures may include conductive housing structures. The housing structures may include a peripheral conductive member that runs around the periphery of an electronic device. The peripheral conductive member may serve as a bezel for a planar structure such as a display, may serve as sidewall structures for a device housing, and/or may form other housing structures. Gaps in the peripheral conductive member may be associated with the antennas.

Electronic device **10** may be a portable electronic device or other suitable electronic device. For example, electronic device **10** may be a laptop computer, a tablet computer, a somewhat smaller device such as a wrist-watch device, pendant device, headphone device, earpiece device, or other wearable or miniature device, a cellular telephone, or a media player. Device **10** may also be a television, a set-top box, a desktop computer, a computer monitor into which a computer has been integrated, or other suitable electronic equipment.

Device **10** may include a housing such as housing **12**. Housing **12**, which may sometimes be referred to as a case, may be formed of plastic, glass, ceramics, fiber composites, metal (e.g., stainless steel, aluminum, etc.), other suitable materials, or a combination of these materials. In some situations, parts of housing **12** may be formed from dielectric or other low-conductivity material. In other situations, housing **12** or at least some of the structures that make up housing **12** may be formed from metal elements.

Device **10** may, if desired, have a display such as display **14**. Display **14** may, for example, be a touch screen that incorporates capacitive touch electrodes. Display **14** may include image pixels formed from light-emitting diodes (LEDs), organic LEDs (OLEDs), plasma cells, electrowetting pixels, electrophoretic pixels, liquid crystal display (LCD) components, or other suitable image pixel structures. A cover glass layer may cover the surface of display **14**. Buttons such as button **19** may pass through openings in the cover glass. The cover glass may also have other openings such as an opening for speaker port **26**.

Housing **12** may include a peripheral member such as member **16**. Member **16** may run around the periphery of device **10** and display **14**. In configurations in which device **10** and display **14** have a rectangular shape, member **16** may have a rectangular ring shape (as an example). Member **16** or part of member **16** may serve as a bezel for display **14** (e.g., a cosmetic trim that surrounds all four sides of display **14** and/or helps hold display **14** to device **10**). Member **16** may also, if desired, form sidewall structures for device **10** (e.g., by forming a metal band with vertical sidewalls, etc.).

Member **16** may be formed of a conductive material and may therefore sometimes be referred to as a peripheral conductive member or conductive housing structures. Member **16** may be formed from a metal such as stainless steel, aluminum, or other suitable materials. One, two, three, or more than three separate structures may be used in forming member **16**.

It is not necessary for member **16** to have a uniform cross-section. For example, the top portion of member **16** may, if desired, have an inwardly protruding lip that helps hold display **14** in place. If desired, the bottom portion of member **16** may also have an enlarged lip (e.g., in the plane of the rear surface of device **10**). In the example of FIG. **1**, member **16** has substantially straight vertical sidewalls. This is merely illustrative. The sidewalls of member **16** may be curved or may have any other suitable shape. In some configurations (e.g., when member **16** serves as a bezel for display **14**), member **16** may run around the lip of housing **12** (i.e., member **16** may cover only the edge of housing **12** that surrounds display **14** and not the rear edge of housing **12** of the sidewalls of housing **12**).

Display **14** may include conductive structures such as an array of capacitive electrodes, conductive lines for addressing pixel elements, driver circuits, etc. Housing **12** may include internal structures such as metal frame members, a planar housing member (sometimes referred to as a midplate) that spans the walls of housing **12** (i.e., a substantially rectangular member that is welded or otherwise connected between opposing sides of member **16**), printed circuit boards, and other internal conductive structures. These conductive structures may be located in the center of housing **12** under display **14** (as an example).

In regions **22** and **20**, openings may be formed within the conductive structures of device **10** (e.g., between peripheral conductive member **16** and opposing conductive structures such as conductive housing structures, a conductive ground plane associated with a printed circuit board, and conductive electrical components in device **10**). These openings may be filled with air, plastic, and other dielectrics. Conductive housing structures and other conductive structures in device **10** may serve as a ground plane for the antennas in device **10**. The openings in regions **20** and **22** may serve as slots in open or closed slot antennas, may serve as a central dielectric region that is surrounded by a conductive path of materials in a loop antenna, may serve as a space that separates an antenna resonating element such as a strip antenna resonating element or an inverted-F antenna resonating element from the ground plane, or may otherwise serve as part of antenna structures formed in regions **20** and **22**.

In general, device **10** may include any suitable number of antennas (e.g., one or more, two or more, three or more, four or more, etc.). The antennas in device **10** may be located at opposing first and second ends of an elongated device housing, along one or more edges of a device housing, in the center of a device housing, in other suitable locations, or in one or more of such locations. The arrangement of FIG. **1** is merely illustrative.

Portions of member **16** may be provided with gap structures. For example, member **16** may be provided with one or more gaps such as gaps **18**, as shown in FIG. **1**. The gaps may be filled with dielectric such as polymer, ceramic, glass, air, other dielectric materials, or combinations of these materials. Gaps **18** may divide member **16** into one or more peripheral conductive member segments. There may be, for example, two segments of member **16** (e.g., in an arrangement with two gaps), three segments of member **16** (e.g., in an arrangement with three gaps), four segments of member **16** (e.g., in an arrangement with four gaps, etc.). The segments of peripheral conductive member **16** that are formed in this way may form parts of antennas in device **10**.

In a typical scenario, device **10** may have upper and lower antennas (as an example). An upper antenna may, for example, be formed at the upper end of device **10** in region **22**. A lower antenna may, for example, be formed at the lower end of device **10** in region **20**. The antennas may be used separately to cover identical communications bands, overlapping communications bands, or distinct non-overlapping communications bands. The antennas may be used to implement an antenna diversity scheme or a multiple-input-multiple-output (MIMO) antenna scheme.

Antennas in device **10** may be used to support any communications bands of interest. For example, device **10** may include antenna structures for supporting local area network communications, voice and data cellular telephone communications, global positioning system (GPS) communications or other satellite navigation system communications, Bluetooth® communications, etc.

A schematic diagram of an illustrative configuration that may be used for electronic device **10** is shown in FIG. **2**. As shown in FIG. **2**, electronic device **10** may include storage and processing circuitry **28**. Storage and processing circuitry **28** may include storage such as hard disk drive storage, nonvolatile memory (e.g., flash memory or other electrically-programmable-read-only memory configured to form a solid state drive), volatile memory (e.g., static or dynamic random-access-memory), etc. Processing circuitry in storage and processing circuitry **28** may be used to control the operation of device **10**. The processing circuitry may be based on one or more microprocessors, microcontrollers, digital signal processors, baseband processors, power management units, audio codec chips, application specific integrated circuits, etc.

Storage and processing circuitry **28** may be used to run software on device **10**, such as internet browsing applications, voice-over-internet-protocol (VOIP) telephone call applications, email applications, media playback applications, operating system functions, etc. To support interactions with external equipment, storage and processing circuitry **28** may be used in implementing communications protocols. Communications protocols that may be implemented using storage and processing circuitry **28** include internet protocols, wireless local area network protocols (e.g., IEEE 802.11 protocols—sometimes referred to as WiFi®), protocols for other short-range wireless communications links such as the Bluetooth® protocol, cellular telephone protocols, etc.

Circuitry **28** may be configured to implement control algorithms that control the use of antennas in device **10**. For example, circuitry **28** may perform signal quality monitoring operations, sensor monitoring operations, and other data gathering operations and may, in response to the gathered data and/or information on which communications bands are to be used in device **10**, control which antenna structures within device **10** are being used to receive and process data and/or may adjust one or more switches, tunable elements, or other adjustable circuits in device **10** to adjust antenna performance. As an example, circuitry **28** may control which of two or more antennas is being used to receive incoming radio-frequency signals, may control which of two or more antennas is being used to transmit radio-frequency signals, may control the process of routing incoming data streams over two or more antennas in device **10** in parallel, may tune an antenna to cover desired communications bands, etc. In performing these control operations, circuitry **28** may open and close switches, may turn on and off receivers and transmitters, may adjust impedance matching circuits, may configure switches in front-end-module (FEM) radio-frequency circuits that are interposed between radio-frequency transceiver circuitry and antenna structures (e.g., filtering and switching circuits used for impedance matching and signal routing), may adjust switches, tunable circuits, and other adjustable circuit elements that are formed as part of an antenna or that are coupled to an antenna or a signal path associated with an antenna, and may otherwise control and adjust the components of device **10**.

Input-output circuitry **30** may be used to allow data to be supplied to device **10** and to allow data to be provided from device **10** to external devices. Input-output circuitry **30** may include input-output devices **32**. Input-output devices **32** may include touch screens, buttons, joysticks, click wheels, scrolling wheels, touch pads, key pads, keyboards, microphones, speakers, tone generators, vibrators, cameras, sensors, light-emitting diodes and other status indicators, data ports, etc. A user can control the operation of device **10** by supplying commands through input-output devices **32** and may receive status information and other output from device **10** using the output resources of input-output devices **32**.

Wireless communications circuitry **34** may include radio-frequency (RF) transceiver circuitry formed from one or more integrated circuits, power amplifier circuitry, low-noise input amplifiers, passive RF components, one or more antennas, and other circuitry for handling RF wireless signals. Wireless signals can also be sent using light (e.g., using infrared communications).

Wireless communications circuitry **34** may include satellite navigation system receiver circuitry such as Global Positioning System (GPS) receiver circuitry **35** (e.g., for receiving satellite positioning signals at 1575 MHz) or satellite navigation system receiver circuitry associated with other satellite navigation systems. Transceiver circuitry **36** may handle 2.4 GHz and 5 GHz bands for WiFi® (IEEE 802.11) communications and may handle the 2.4 GHz Bluetooth® communications band. Circuitry **34** may use cellular telephone transceiver circuitry **38** for handling wireless communications in cellular telephone bands such as bands in frequency ranges of about 700 MHz to about 2700 MHz or bands at higher or lower frequencies. Wireless communications circuitry **34** can include circuitry for other short-range and long-range wireless links if desired. For example, wireless communications circuitry **34** may include global positioning system (GPS) receiver equipment or other satellite navigation system equipment, wireless circuitry for receiving radio and television signals, paging circuits, etc. In WiFi® and Bluetooth® links and other short-range wireless links, wireless signals are typically used to convey data over tens or hundreds of feet. In cellular telephone links and other long-range links, wireless signals are typically used to convey data over thousands of feet or miles.

Wireless communications circuitry **34** may include one or more antennas **40**. Antennas **40** may be formed using any suitable antenna types. For example, antennas **40** may include antennas with resonating elements that are formed from loop antenna structure, patch antenna structures, inverted-F antenna structures, closed and open slot antenna structures, planar inverted-F antenna structures, helical antenna structures, strip antennas, monopoles, dipoles, hybrids of these designs, etc. Different types of antennas may be used for different bands and combinations of bands. For example, one type of antenna may be used in forming a local wireless link antenna and another type of antenna may be used in forming a remote wireless link.

A top interior view of device **10** in a configuration in which device **10** has a peripheral conductive housing member such as housing member **16** of FIG. **1** with one or more gaps **18** is shown in FIG. **3**. As shown in FIG. **3**, device **10** may have an antenna ground plane such as antenna ground plane **52**. Ground plane **52** may be formed from traces on printed circuit boards (e.g., rigid printed circuit boards and flexible printed circuit boards), from conductive planar support structures in the interior of device **10**, from conductive structures that form exterior parts of housing **12**, from conductive structures that are part of one or more electrical components in device **10** (e.g., parts of connectors, switches, cameras, speakers, microphones, displays, buttons, etc.), or other conductive device structures. Gaps such as gaps **82** may be filled with air, plastic, or other dielectric.

One or more segments of peripheral conductive member **16** may serve as part of the conductive structures for an antenna in device **10**. For example, the lowermost segment of peripheral conductive member **16** in region **20** may serve as part of the conductive structures for an antenna in device **10**. These structures may be provided with switches and other adjustable components or may be provided with fixed components. In arrangements in which an antenna is provided with adjustable components, the antenna may be tuned during operation to cover communications bands of interest. Tunable antennas **40** in device **10** may be implemented using antenna structures in region **22** and/or region **20**. Illustrative tunable antenna structures of the type that may be used in region **20** are sometimes described herein as an example.

An illustrative antenna **40** that has been implemented in region **20** of device **10** is shown in FIG. **4**. Antenna **40** of FIG. **4** may have an antenna feed such as antenna feed **106**. Antenna feed **106** may have a positive antenna feed terminal such as positive antenna feed terminal **92** (+) and a ground antenna feed terminal such as ground antenna feed terminal **94** (–). Wireless circuitry such as radio-frequency transceiver circuitry **108** (e.g., transceiver circuitry such as circuitry **38** of FIG. **2** or other suitable radio-frequency transceiver circuitry) may be coupled to antenna feed **106** using signal paths such as path **90**. Path **90** may include one or more transmission lines such as coaxial cable transmission lines, microstrip transmission lines, stripline transmission lines, or other transmission line structures. As shown in FIG. **4**, path **90** may include a positive signal conductor such as conductor **90**P and a ground signal conductor such as conductor **90**N. Impedance matching circuits, filters, switches, and other circuits may be interposed within path **90**, if desired.

Conductive structures **52** may form part of antenna (e.g., an antenna ground plane). Antenna **40** may also include conductive structures such as conductive arm **96** and a conductive arm formed from peripheral conductive member **16**. Conductive arm **96** may be formed from a strip of metal or other conductive materials. Conductive arm **96** may, for example, be formed from a patterned metal trace on a flexible printed circuit, rigid printed circuit, plastic support structure, or other substrate. Arm **96** may have an L-shape, a shape with two or more straight segments, a shape with curved segments or a combination of curved and straight segments, or other suitable shape. Antenna feed **106** may be coupled between arm **96** and conductive ground plane structures **52**. Inductor L**2** (e.g., a discrete inductor component such as a surface mount technology component or other inductive element) may be coupled between arm **96** and ground plane structures **52** at a first end of arm **96**. Another inductor such as inductor L**1** may be coupled to an opposing second end of arm **96**.

A circuit such as tunable circuit **98** may be interposed in arm **96**. Circuit **98** may include one or more adjustable components that may be used in tuning antenna **40**. As shown in FIG. **4**, for example, circuit **98** may include a capacitor such as capacitor C**2** (e.g., a tunable capacitor or a fixed capacitor) and a bypass switch such as switch SW**2**. Circuit **98** may have a first terminal such as terminal **100** and a second terminal such as terminal **102**. Capacitor C**2** and switch SW**2** may be coupled in parallel between terminals **100** and **102**. The state of switch SW**2** may be controlled by control signals from control circuitry in device **10** such as storage and processing circuitry **28** (e.g., a baseband processor). Switch control signals may be provided to switch SW**2** over a control signal path such as path **104**. When switch SW**2** is open, capacitance C**2** (e.g., a fixed or variable capacitance) may be interposed in arm **96**. When switch SW**2** is closed, capacitance C**2** may be bypassed. Other types of adjustable capacitance circuitry may be interposed in arm **96** if desired. The example of FIG. **4** is merely illustrative.

Peripheral conductive member **16** may form a conductive path (arm) that is shorted to antenna ground **52** at one end (e.g., on the left-hand side of gap **82** at location **101**) and that is separated from ground **52** (e.g., portions of member **16** that are shorted to ground **52**) at another end (e.g., at gap **18**). Gap **18** may give rise to a parasitic capacitance C**1** between the end of arm **96** and ground structure **52**.

An antenna tuning circuit such as a circuit formed from inductor L**1** and switch SW**1** may bridge gap **18**. The state of switch SW**1** may be controlled by control signals from control circuitry in device **10** such as storage and processing circuitry **28** (e.g., a baseband processor). Switch control signals may be provided to switch SW**1** over a control signal path such as path **106**. When switch SW**1** is open, inductor L**1** may be coupled across gap **18** in parallel with parasitic capacitance C**1**. When switch SW**1** is closed, inductor L**1** and capacitance C**1** may be bypassed by the short circuit formed by switch SW**1** (i.e., gap **18** may be temporarily bridged by the short circuit formed by switch SW**1**).

Antenna tuning adjustments may be made to antenna **40** to configure antenna **40** to cover desired operating frequencies. The frequency response of antenna **40** may be tuned by adjusting adjustable components in antenna **40** such as capacitor C**2**, switch SW**2**, and switch SW**1**. If desired, additional adjustable circuitry may be used (e.g., adjustable matching circuits, additional switches in antenna **40**, etc.).

The way in which antenna **40** of FIG. **4** operates may be understood with reference to FIGS. **5-14**, which show how antenna **40** of FIG. **4** may be constructed by adding progressively more components to an inverted-F antenna (i.e., antenna **40'** of FIG. **5**).

As shown in FIG. **5**, antenna **40'** may have an antenna resonating element such as antenna resonating element **118** and a ground structure such as ground **52**. Antenna resonating element **118** may have a main resonating element arm such as arm **96**. Short circuit branch **114** may couple arm **96** to ground **52**. Antenna feed **106** may contain positive antenna feed terminal **92** (+) and ground antenna feed terminal **94** (–). Antenna feed **106** may be formed using a branch of antenna resonating element **118** that couples arm **96** to ground **52**.

FIG. **6** is a graph of antenna performance (standing wave ratio) as a function of operating frequency for an antenna such as inverted-F antenna **40'** of FIG. **5**. As shown by curve **120** of FIG. **6**, antenna **40'** of FIG. **5** may exhibit a resonance in a communications band centered on frequency fc. During operation, signals in this communications band may be transmitted and received using antenna **40'**.

If desired, short circuit branch **114** of antenna resonating element **118** in antenna **40'** may be implemented using a discrete component such as a surface mount technology (SMT) inductor or other inductor. This type of configuration for antenna **40'** is shown in FIG. **7**. As shown in FIG. **7**, inductor L**2** may be coupled between arm **96** and ground **52** in place of short circuit branch **114** of FIG. **5** (e.g., at the leftmost end of arm **96** in the orientation of FIG. **7**). Branch **114** of FIG. **5** may be characterized by a finite inductance. The resulting frequency response of antenna **40'** when inductor L**2** of FIG. **7** is used in place of short circuit branch **114** of FIG. **5** may therefore still be characterized by a curve such as curve **120** of FIG. **6**.

If desired, antenna **40'** may be provided with a parasitic antenna resonating element such as L-shaped parasitic antenna resonating element **16** of FIG. **8** (e.g., a portion of peripheral conductive member **16** of FIG. **4**). Parasitic antenna resonating element **16** may, for example, have an arm that runs parallel to arm **96**. The lengths of the L-shaped parasitic antenna resonating element arm and the inverted-F antenna resonating element arm in antenna **40'** may be different. For example, parasitic antenna resonating element arm **16** may be longer than arm **96**. This may help to broaden the frequency response of antenna **40'**.

FIG. **9** is a graph of antenna performance (standing wave ratio) as a function of operating frequency for an antenna such as inverted-F antenna **40'** of FIG. **8**. Parasitic antenna resonating element **16** may be characterized by a resonance such as the resonance of curve **124**, centered at frequency fb. In the absence of parasitic antenna resonating element **16**, antenna

40' (i.e., antenna resonating element arm 96) may be characterized by curve 126, which exhibits a resonance centered at frequency fc. When inverted-F antenna resonating element arm 96 and parasitic antenna resonating element 16 are both present, as in FIG. 8, antenna 40' may exhibit a response of the type shown by curve 128. Because curve 128 is influenced by both the shorter antenna arm (resonating element arm 96) and the longer antenna arm (parasitic antenna resonating element arm 16), the resonance of curve 128 may be broader than the resonance of curve 120 of FIG. 6.

As shown in FIG. 10, antenna 40' may be provided with a tunable circuit such as tunable circuit 98 in arm 96 and may have conductive structures such as conductive path 130 that couples antenna resonating element arm 96 to arm 16. Circuit 98 may include a capacitor such as capacitor C2. Capacitor C2 may be a fixed capacitor or may be a variable capacitor. Switch SW2 may be used to selectively bypass capacitor C2. Circuit 98 may be formed using one or more components. For example, capacitor C2 and switch SW2 may be formed using individual components or may be formed using a single unitary part.

FIG. 11 is a graph of antenna performance (standing wave ratio) as a function of operating frequency for an antenna such as antenna 40' of FIG. 10. In the absence of capacitor C2, antenna 40' may be characterized by curve 128 (i.e., curve 128 of FIG. 9). When capacitance C2 is present, however, antenna 40' may be characterized by narrower curve 132. If, for example, curve 128 is characterized by frequency resonance peaks fb (from element 16) and fc (from element 96), curve 132 may be characterized by frequency response peaks at frequency fb' (i.e., a frequency greater than fb) and at frequency fc' (i.e., a frequency less than fc). Capacitance C2 may be switched into use (e.g., by opening switch SW2) to ensure that the response of antenna 40' matches a desired communications band of interest (e.g., so that antenna 40' exhibits the narrower resonance of curve 132 of FIG. 11). In configurations in which capacitance C2 is variable, the magnitude of capacitance C2 may be adjusted to adjust the width of curve 132.

As shown in FIG. 12, when capacitor C1 (e.g., a parasitic capacitance associated with gap 18 of FIG. 4), inductor L1, and switch SW1 are coupled between tip 132 of arm 96 (and/or an associated portion of arm 16) and ground (e.g., across gap 18 of FIG. 4), antenna 40' of FIG. 10 may have the configuration of antenna 40 of FIG. 4 (i.e., antenna 40 of FIG. 12 may be implemented using structures of the type shown in FIG. 4). If desired, antenna 40 of FIG. 12 may be implemented using other structures. The antenna structures and circuitry of FIG. 4 are merely an illustrative example of structures and circuits that can be used in implementing antenna 40 of FIG. 12.

FIGS. 13 and 14 are graphs showing how antenna 40 of FIG. 12 may perform as a function of operating frequency and how antenna 40 may be tuned by controlling the states of switches SW1 and SW2. FIG. 13 is a graph of antenna performance (standing wave ratio) as a function of operating frequency for an antenna such as antenna 40 of FIG. 12 in a configuration in which switches SW1 and SW2 are both open. Operating frequencies from about 700-960 MHz may correspond to a "low" communications band for antenna 40 (as an example). In this low band, inductor L1 and capacitance C1 may form a resonant circuit with a relatively large impedance (i.e., inductor L1 and C1 may form an open circuit at frequencies in the range of 700-960 MHz). Because the circuit formed by L1 and C1 is effectively open and because switch SW1 is open, the shape of low band curve portion 136 of FIG. 13 may match that of curve 132 in FIG. 11 (the shape of which may be tuned by adjusting capacitance C2 in configurations for antenna 40 in which capacitor C2 is a variable capacitor). At higher frequencies (e.g., frequencies in the vicinity of 2300 MHz to 2700 MHz or other suitable frequency range), antenna 40 of FIG. 12 may exhibit a resonant peak such as resonant peak 138 (i.e., antenna 40 may exhibit performance satisfactory for handling communications at frequencies from 2300 MHz to 2700 MHz while switches SW1 and SW2 are open).

When it is desired to cover lower high-band frequencies such as frequencies from 1710 MHz to 2170 MHz (or other suitable frequency range), control circuitry in device 10 may be used to close switches SW1 and SW2. In this configuration, antenna 40 of FIG. 12 may exhibit a response of the type shown by curve 140 of FIG. 14. The response of curve 140 may be influenced by contributions from two different loop antenna modes in antenna 40 of FIG. 12. As shown in FIG. 12, antenna 40 may, have a first (longer) loop antenna mode associated with loop-shaped signal path 148 and may have a second (shorter) loop antenna mode associated with loop-shaped signal path 150 of FIG. 12. The shorter loop antenna mode may give rise to resonant contribution 144 of curve 140 of FIG. 14. The longer loop antenna mode may give rise to resonant contribution 142 of curve 140 of FIG. 14.

In the illustrative configuration of FIG. 12, antenna 40 has actively adjusted components such as switches SW1 and SW2 for ensuring that antenna 40 exhibits a desired response as a function of frequency. If desired, passive switching techniques may be used to perform switching in antenna 40. For example, an arrangement of the type shown in FIG. 15 may be used for antenna 40 in which switch SW1 is replaced by resonant circuit 146. Resonant circuit 146 and capacitor C1 may be configured to form a resonant circuit with an impedance that changes as a function of frequency. Circuit 146 may be configured so that a short circuit is formed across gap 18 at frequencies from 1710 MHz to 2170 MHz (or other suitable frequency range) and to form a high impedance (e.g., an open circuit) at other frequencies (e.g., the low band and/or the high band of FIG. 13). When configured in this way, circuit 146 can form a short circuit of the type formed by closed switch SW2 of FIG. 12 during operation at 1710 MHz to 2170 MHz (e.g., to produce curve 140 of FIG. 14) and can form an open circuit at other frequencies such as the frequencies associated with the low band (700-960 MHz) and high band (2300-2700 MHz) (e.g., to produce curves 136 and 138 of FIG. 13).

The foregoing is merely illustrative of the principles of this invention and various modifications can be made by those skilled in the art without departing from the scope and spirit of the invention.

What is claimed is:

1. An antenna, comprising:
- a ground plane;
- a first arm that has opposing first and second ends, that includes first and second segments, and that is electrically coupled to the ground plane;
- an antenna feed coupled between the ground plane and the second end of the first arm;
- a tunable circuit interposed in the first arm between the first and second segments;
- a second arm having a first end that is directly connected to the first end of the first arm and having a second end that is coupled to the ground plane; and
- an inductor that electrically couples the second end of the first arm to the ground plane.

2. The antenna defined in claim 1 further comprising a switch that is coupled between the end of the first arm and the ground plane.

3. The antenna defined in claim **1** wherein the tunable circuit comprises a variable capacitor.

4. The antenna defined in claim **1** wherein the tunable circuit comprises a capacitor.

5. The antenna defined in claim **1** wherein the tunable circuit comprises a switch and a capacitor in parallel with the switch.

6. The antenna defined in claim **1** wherein the tunable circuit comprises a first switch and a capacitor in parallel with the first switch, the antenna further comprising a switch that is coupled between the end of the first arm and the ground plane.

7. The antenna defined in claim **1** wherein the second arm comprises at least part of a peripheral conductive member that runs around at least some edges of a housing for an electronic device.

8. The antenna defined in claim **7** further comprising a gap in the peripheral conductive member, wherein the antenna further comprises an inductor that bridges the gap.

9. The antenna defined in claim **8** further comprising a switch that bridges the gap.

10. The antenna defined in claim **8** further comprising a first switch that bridges the gap, wherein the tunable circuit comprises a second switch and a capacitor in parallel with the second switch.

11. An antenna, comprising:

an antenna ground;

a resonating element arm having opposing first and second ends;

an antenna feed coupled between the antenna ground and the resonating element arm;

a first inductor that is coupled between the resonating element arm and the antenna ground at the first end;

a peripheral conductive member that runs around at least some edges of a conductive housing for an electronic device, wherein portions of the peripheral conductive member are separated from the antenna ground by first and second gaps that create respective parasitic capacitances between the peripheral conductive member and the antenna ground and that divide the peripheral conductive member into at least three segments; and

a second inductor that is coupled between the peripheral conductive member and the antenna ground and that bridges the second gap.

12. The antenna defined in claim **11** further comprising a switch that is coupled in parallel with the second inductor.

13. The antenna defined in claim **11** further comprising a switch that is coupled in parallel with the second inductor and the second gap.

14. The antenna defined in claim **13** wherein the peripheral conductive member has a first portion that is electrically connected to the antenna ground and a second portion that is separated from the antenna ground by the second gap, and the second end of the antenna resonating element arm is coupled to the second portion of the peripheral conductive member.

15. The antenna defined in claim **11** further comprising a tunable circuit that is interposed in the antenna resonating element arm.

16. The antenna defined in claim **15** wherein the tunable circuit includes a capacitor.

17. An antenna, comprising:

an antenna ground;

a peripheral conductive member that runs around at least two external edges of a housing for an electronic device;

a resonating element arm having a first end that is coupled to the antenna ground and a second end that is coupled to the peripheral conductive member;

an antenna feed coupled between the ground plane and the resonating element arm; and

a switch that is coupled between the peripheral conductive member and the antenna ground.

18. The antenna defined in claim **17** wherein the peripheral conductive member is separated from the antenna ground by at least one gap that creates a parasitic capacitance between the peripheral conductive member and the antenna ground and wherein the switch bridges the gap.

19. The antenna defined in claim **18** further comprising a capacitor interposed in the antenna resonating element arm.

20. The antenna defined in claim **19** further comprising an additional switch that bridges the capacitor.

21. The antenna defined in claim **20** further comprising:

an inductor coupled in parallel with the switch.

22. The antenna defined in claim **1**, wherein the tunable circuit is interposed in the first arm at a location between the antenna feed and where the first end of the first arm and the first end of the second arm are directly connected.

23. The antenna defined in claim **17**, wherein the peripheral conductive member has portions that are separated from the antenna ground by first and second gaps that create respective parasitic capacitances between the peripheral conductive member and the antenna ground and divide the peripheral conductive member into at least three segments.

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